Journal of University of Science and Technology Beijing
Volume 10, Number 6, December 2003, Page 44

Materials

Heat transfer analysis for the roller shell under the condition of periodic thermal shock

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(Received 2003-02-05)

Abstract: According to the actual working conditions of roller shell in the process of continuous roll casting, the Fourier heat transfer law is used to conduct the simulating analysis for the temperature distribution of the roller shell under the condition of periodic thermal shock. The temperature variation law inside the roller shell is studied during the process of continuous roll casting, and the steady temperature distributions of the roller shell at different casting velocities have been obtained when the thermal contact conductance between the roller shell and the casting strip is considered.

Key words: roller shell; thermal contact conductance (TCC); periodic thermal shock

[*This work was supported by the State Key Project of Fundamental Research (No.199906496).*]

Roller shell is the key part of continuous roll casting process, and its life will directly influence the productivity of the roller. The alternately exchanged thermal stress, which induced by the uneven temperature field in the contact process between the roller and the strip, is the main reason for the destroying of the casting roller.

Contact conditions between the casting roller and the strip during continuous roll casting process are extremely complex [1, 2]. The contact heat transfer coefficient is usually regarded as a constant or neglected when carrying out the temperature field simulation during continuous roll casting process in the past. Because the conditions of the contact surfaces are complicated and all the factors, such as surface temperature, rolling force, surface morphology *etc.*, which related to the contact surfaces are interactive, the heat transfer mechanism in the interface has not been completely understood till now [3]. The imperfect contact in the interface between the strip and the roller, which results in heat flux constriction in the process of heat transfer, is usually regarded as the primary cause of thermal contact conductance [4]. The influencing factors continuously change during the heat transfer process, so the real thermal contact conductance changes with them. The method of considering the thermal contact conductance as a constant or neglecting it is not suitable. In the present analysis the thermal contact conductance is considered when carrying out the heat transfer calculation of the roller shell. The variation laws of temperature fields of the roller shell were studied during the heat transfer processes, the steady temperature distributions at different rolling velocities were obtained.

1 Physical model for the heat transfer process of the roller shell

The casting roller periodically rotates around its axis in the real operation [5], the molten metal is cooled and then rolled into strip. In order to simplify the calculation, the coordinate system is set on the roller, and the casting strip is considered as a linear heat source to move periodically around the roller. Its physical model is shown in **figure 1**.

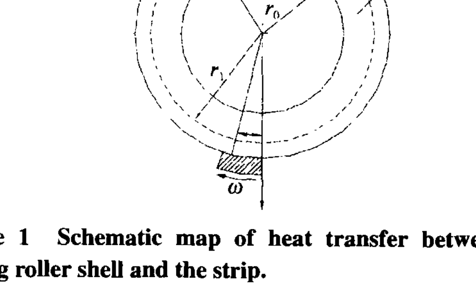

Figure 1 Schematic map of heat transfer between the casting roller shell and the strip.

2 Governing equations

According to the Fourier heat transfer law, the basic heat transfer equation of the roller shell is deduced by using micro-elemental energy conversation theory,

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that is:

$$a\left(\frac{\partial t^2}{\partial r^2}+\frac{1}{r}\frac{\partial t}{\partial r}+\frac{1}{r^2}\frac{\partial t^2}{\partial \theta^2}+\frac{\partial t^2}{\partial z^2}\right)-\left(v_r\cdot\frac{\partial t}{\partial r}+v_\theta\cdot\frac{1}{r}\cdot\frac{\partial t}{\partial \theta}+v_z\cdot\frac{\partial t}{\partial z}\right)+S_t=\frac{\partial t}{\partial \tau} \tag{1}$$

where t is the temperature of the roller shell, K; $a=k/(\rho\cdot c)$ the thermal diffusivity of the casting roller, m^2/s; k the thermal conductivity, W/(m·K); c the specific heat capacity, J/(g·K); ρ the density of the roller shell, g/cm^3; v_r, v_θ, v_z the velocity in the r, θ, z coordinate direction, respectively; S_t the heat resource; τ represents time.

Set the coordinate system on the center of the roller, then the roller shell can be regard as staying in static state and the heat resource S_t can also be neglected. At the same time, since the width to the thickness ratio is large enough, it is supposed that the temperature distribution has nothing to do with the axial direction (z), then equation (1) can be expressed as:

$$a\left(\frac{\partial t^2}{\partial r^2}+\frac{1}{r}\frac{\partial t}{\partial r}+\frac{1}{r^2}\frac{\partial t^2}{\partial \theta^2}\right)=\frac{\partial t}{\partial \tau} \tag{2}$$

3 Boundary conditions

3.1 Natural convective and radiant heat transfer between the roller shell surface and the atmosphere [6]

$$h_f\cdot(t_f-t)=-k\frac{\partial t}{\partial r} \tag{3}$$

where h_f is the natural convective and radiant heat transfer coefficient of the roller shell surface, W/(m^2·K), $h_f=h_c+h_r$; h_c the convective heat transfer coefficient, W/(m^2·K); h_r the radiant heat transfer coefficient, W/(m^2·K); t_f the ambient temperature, K; d the outside diameter of the casting roller, m; k the thermal conductivity of the roller shell material, W/(m·K).

3.2 Forced convective heat transfer between the inside surface of the casting roller shell and the cooling water [7]

$$h_w\cdot(t_{f2}-t)=-k\frac{\partial t}{\partial r} \tag{4}$$

$$h_w=0.023\frac{k_w}{d_1}Re_f^{0.8}Pr_f^{0.4}$$

where h_w is the heat transfer coefficient between the inside surface of the roller shell and the cooling water, W/(m^2·K); t_{f2} the average temperature of the cooling water, K; Re_f the Renold number of the cooling water, $Re_f=\omega\cdot d_1/v$; Pr_f the Prantal number of the cooling water, $Pr_f=c_\omega\eta/k_\omega$; ω the flow velocity of the cooling water, m/s; v the kinematic viscosity of the cooling water, m^2/s; c_ω the specific heat capacity of the cooling water, J/(g·K); η the viscosity of the cooling water, Pa·s; k_w the thermal conductivity of the cooling water, W/(m·K); d_1 the equivalent diameter of the cooling water channel, m.

3.3 Heat transfer in the contact interface between the casting roller shell and the strip

(1) Thermal contact conductance in the contact zone between the roller shell and the strip.

The calculation of the thermal contact conductance in the contact zone is divided into two areas: rolling zone and crystallization zone.

(a) The rolling zone.

The characteristics in the contact interface of continuous roll casting process are 1) high temperature, 2) high pressure and 3) relative sliding between the contact interface. The dramatic plastic deformation occurs in the rolling zone, then the TCC (thermal contact conductance) value is calculated according to reference [8], that is:

$$h_a=h^*\cdot k_m/\sigma \tag{5}$$

$$h^*=1.57\times10^{-3}\cdot(p^*)^{0.84}+0.92\times10^{-3} \tag{6}$$

where h_a is the thermal contact conductance of the interface, W/(m^2·K); h^* the dimensionless thermal contact conductance; p^* the dimensionless contact pressure; σ the RMS roughness, m, σ_1 and σ_2 are the RMS roughness of the two contact materials, respectively; p the interfacial contact pressure, MPa; k_m the average thermal conductivity of the two contact material, $\frac{2}{k_m}=\frac{1}{k_1}+\frac{1}{k_2}$; k_1 and k_2 are the thermal conductivity of the contact materials, respectively, W/(m·K).

(b) The crystallization zone.

The TCC value in the crystallization is calculated in reference [9]:

$$h^*=0.075\times(P^*)^{0.672} \tag{7}$$

(2) Heat transfer in the contact interface of the roller shell and the strip.

The third kind of the boundary condition is adapted to describe the heat transfer in the interface.

$$h_a\cdot(t_c-t)=-k\frac{\partial t}{\partial n} \tag{8}$$

where t_c is the temperature of the strip contact with the roller shell, K.

4 Boundary conditions under the condition of periodic thermal shock

Owing to the periodic rotation of the roller, the outside surface of the roller suffered the periodic thermal shock by the thermal strip [10], the temperature distribution function in the contact zone is:

$$t_c = f(r,\theta) \quad (9)$$

The rotating velocity of the outside surface of the roller is V_r, relative to every merging time step $\Delta\tau$, then the moving distance of the strip around the roller is $V_r \cdot \Delta\tau$. It is defined that N times $V_r \cdot \Delta\tau$ equals to $d \cdot \Delta\theta / 2$, that is:

$$V_r \cdot \Delta\tau \cdot N = d \cdot \Delta\theta / 2 \quad (10)$$

When the strip rotates around the boundary node point of the roller in a circle, the boundary nodes stay in several different conditions, respectively:

(1) Only the convective and the radiant heat transfer between the boundary node i and the atmosphere occur when the boundary node i stay far away from the strip, then at node i of the outside surface of the roller shell, the heat transfer flux in unite time is:

$$Q_i = \frac{d}{2} \cdot \Delta\theta \cdot h_f (t_f - t_i) \quad (11)$$

(2) The convective and the radiant heat transfer occur in the $(N-m)/N$ contact part between the boundary node i and the atmosphere, another m/N part of the boundary node i has convective heat transfer with the strip when the boundary node i stays near to or just enter into the contact zone:

$$Q_i = [(N-m)/N] \cdot \frac{d}{2} \cdot \Delta\theta \cdot h_f (t_f - t_i) + (m/N) \cdot \frac{d}{2} \cdot \Delta\theta \cdot h_a (t_c - t_i) \quad (N>m>0) \quad (12)$$

(3) Only the convective heat transfer occurs between node i and the strip when node i completely enter into the contact zone:

$$Q_i = (d/2) \cdot \Delta\theta \cdot h_a (t_c - t_i) \quad (13)$$

(4) The situation just the same as condition (2) when node i is going to or just leave the contact zone, that is:

$$Q_i = [(N-m)/N] \cdot \frac{d}{2} \cdot \Delta\theta \cdot h_f (t_f - t_i) + (m/N) \cdot \frac{d}{2} \cdot \Delta\theta \cdot h_a (t_c - t_i) \quad (N>m>0) \quad (14)$$

where $m \cdot V_r \cdot \Delta\tau$ is the length of the contact zone between the strip and the boundary node i of the roller shell.

5 Differential calculation

The roller shell is divided into $i \times j$=124×6 grids (as shown in **figure 2**), where i represents the grid nodes divided around the circumferential direction of the shell and j represents the grid nodes divided along the radial direction of the shell.

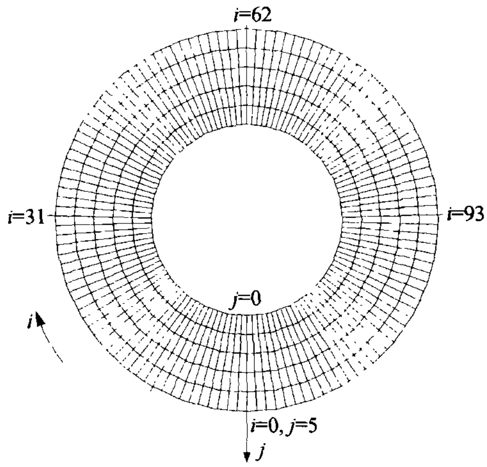

Figure 2 Grids map for the roller shell.

The center differential scheme is used to discretize the governing equation, the initial and the boundary conditions. The basic technological parameters are shown in **table 1**.

Table 1 Technological parameters for the temperature simulation of the roller shell

Parameter	Relative value
Rolling velocity / (m·min^{-1})	0.9, 3.6, 9.0
Diameter of the shell / cm	100
Thickness of the shell / cm	5
Heat transfer coefficient of the shell / (W·cm^{-2}·K^{-1})	0.3606
Density of the shell / (g·cm^{-3})	7.9
Specific heat capacity of the shell / (J·g^{-1}·K^{-1})	2.49
Temperature of cooling water / K	298
Ambient temperature / K	298

6 Results and analysis

Through mathematic calculation, the steady temperature distributions on the outside surface of the roller shell at different rolling velocities are obtained (as shown in **figure 3**).

Figure 3 shows that the temperature of the roller shell is higher near the contact zone, with the rotation of the roller, the temperature gradually decreases, and reaches the lowest value when comes to the entrance of the strip. The biggest temperature difference in the outside surface of the shell deceases with the improvement of the rolling velocity when the rolling velocity is 0.9, 3.6 and 9.0 m/min, the highest temperature of the shell reaches 499.24°C, 319.23°C and 44.22°C, respectively and the lowest temperature is 99.92°C, 174.02°C and 188.86°C, separately.

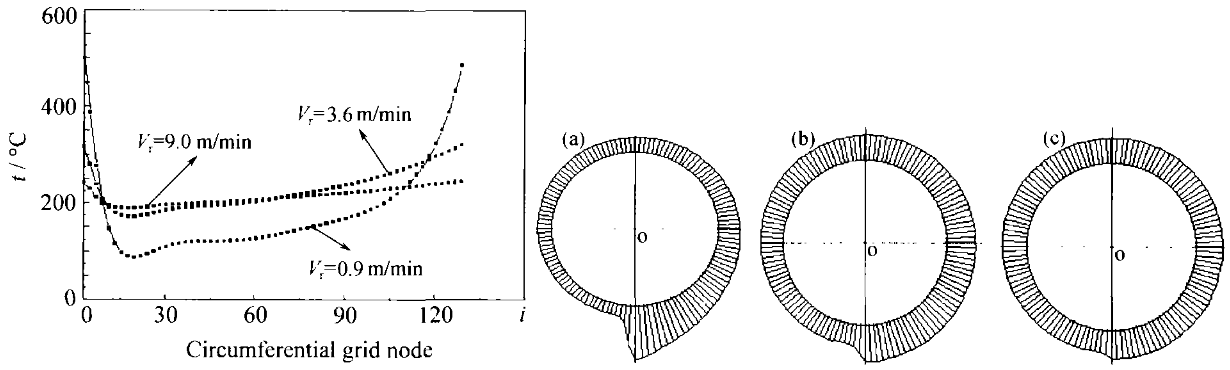

Figure 3 Temperature distributions on the outside surface of the roller shell at different rolling velocities, (a)*V*=0.9 m/min; (b)*V*=3.6 m/min; (c)*V*=9.0 m/min.

Figure 4 depicts the temperature distribution conditions of the roller shell at different rolling velocities. It shows that (1) the temperature distribution gradually reaches even with the improvement of the rolling velocities; (2) the temperature different between the outside and the inside surface of the shell gradually decreases when the rolling velocity is 0.9, 3.6, and 9.0 m/min, respectively, the biggest temperature difference in the outside and inside surface of the roller shell is 469.34°C, 289.43°C and 214.32°C, respectively.

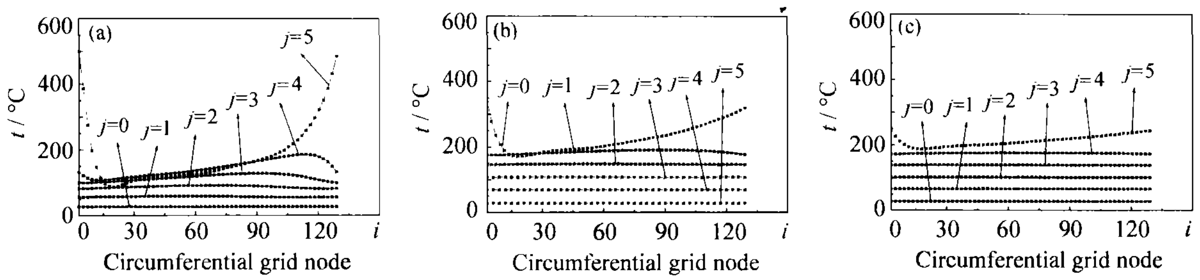

Figure 4 Temperature distributions of the roller shell at different rolling velocities, (a) *V*=0.9 m/min; (b) *V*=3.6 m/min; (c) *V*=9.0 m/min.

7 Conclusions

(1) The third kind of the boundary condition is adopted, that is the thermal contact conductance in contact zone between the roller shell and the strip is considered and the two-dimensional cylinder coordinate heat transfer model is used in the simulation for the temperature distribution of the roller shell.

(2) Through simulation analysis the steady temperature distribution laws are obtained at different rolling velocities. The biggest temperature difference in the outside surface of the roller shell gradually decreases with the improvement of the rolling velocity; meanwhile, the temperature distribution reaches even with the improvement of the rolling velocity and the biggest temperature difference in the outside and inside surface of the roller shell decreases.

References

[1] M.A. Lambert and L.S. Fletcher, Thermal contact conductance of spherical rough metals [J], *J. Heat Transfer*, 119(1997), p.684.

[2] L.S. Fletcher, Recent development in contact conductance heat transfer [J], *J. Heat Transfer*, 110(1988), p.1059.

[3] M.R. Sridhar and M.M. Yovanovich, Thermal contact conductance of tool steel and comparison with model [J], *In. J. Heat Transfer*, 39(1996), No.4, p.831.

[4] C.V. Madhusudana and L.S. Fletcher, Contact heat transfer-the last decade [J], *AIAA J.*, 24(1986), No.3, p.510.

[5] X.L. Ma, *Continuous Roll Casting Produce of Aluminium Strip* (in Chinese) [M]. Publication of Center South University, Changsha, 1992.

[6] Z.R. Zhang, *Heat Transfer* (in Chinese) [M]. Publication of Higher Education, Beijing, 1989.

[7] J.Q. Sun, H.J. Li, and X.Z. Zhang, Study on heat transfer between roller and slab in continuous casting machine [J], *J. Iron Steel Res.* (in Chinese), 9(1997), No.3, p.10.

[8] L.H. Zhan, *Experiment and Modeling for the Thermal Contact Resistance and Its Application in the Parameter Design of Fast Roll Casting* (in Chinese) [D], Central South University, 2001.

[9] X.Q. Li, S.C. Hu, W.F. Xiao, *et al.*, Simulation for the thermal contact conductance and the temperature distribution of the strip in the roll casting zone in the fast roll casting process [J], *Heavy Mach.* (in Chinese), 1999, No.3, p.34.

[10] T. Liang, J. Zhong, W.M. Wand, *et al.*, Simulation for the temperature field of roller shell [J], *Heavy Mach.* (in Chinese), 2001, No.1, p.31.